

**WAMI – A MENU-DRIVEN COMPUTER PROGRAM FOR
THE ESTIMATION OF WEIGHT AND MOMENTS OF INERTIA
OF EARTH-TO-ORBIT TRANSPORTS**

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ABSTRACT

A program, entitled Weights, Areas, and Mass Properties (or WAMI) is centered around an array of menus that contain constants that can be used in various mass estimating relationships for the ultimate purpose of obtaining the mass properties of Earth-to-Orbit Transports. The current Shuttle mass property data was relied upon heavily for baseline equation constant values from which other options were derived.

Background

Characterization of the mass properties of any Earth-to-Orbit transport is complicated by the enormous amount of detail that is needed to support the end result – the end result principally being weights and centers of gravity for the various stages of any one mission. In the WAMI program, menus are provided containing a number of options for constants for each subsystem. Usually, one of the menu options is based on the current Shuttle. Additional values are based on various technological and configurational assumptions.

The menu system to obtain mass properties facilitates both the work of the user and the ability of the recipient in understanding the results. In using Shuttle data for the calculation of the basic constants, the fidelity of the mass estimating equations is enhanced. It is not practical, at least at the conceptual level, to identify all of the non-optimum weights that should be assigned to a given subsystem. For example, analytic solutions for structure are still needed to identify innovative configurations and to demonstrate the utility of new materials. However, the so-called ‘stress’ wing is typically only about one half the weight of the ‘real’ wing. By utilizing Shuttle mass properties as a base, data for realistic values for non-optimums and the all-up structure are obtained.

For Earth-to-Orbit transports, intimate knowledge of ascent aerodynamics is not a critical factor. One exception is ascent drag, variations of which yield modest changes in orbital deliverable

payload. However, very accurate values for inert mass at main engine cut-off (MECO) are critical. Inaccurate predictions for weight growth are widely known for eliminating many planned useful payloads.

For the return to Earth, unlike ascent, balance (i.e., c.g. location) is critical. In concept development, a proposed vehicle with poorly developed mass properties is just as useless as one with the same treatment for aerodynamics. If the c.g. is incorrectly placed, this may mean that the wing must be moved, its leading edge sweep changed, or its size (mass) changed. In using a menu system for mass estimating constants, the program recipient should better understand the mass properties assumptions; and by base-lining constants on the current Shuttle, the risk of substantial weight growth is minimized. Overall, enormous savings in structural weight accrue by simplification of vehicle configuration. This includes the use of integral main propellant tanks, circular body cross-sections, and a flush mounted crew cabin canopy [1].

Mission Inputs

The following are the mission inputs that are required to run the program. They include payload related items such as volume, on-orbit maneuvering delta-V, mission duration, number of crew, and propellant loading as a fraction of fully loaded vehicle at lift-off. The required vehicle-propellant fraction must come from a trajectory program that has some reasonable assumptions for vehicle drag and exact assumptions for orbital destination such as orbital inclination and altitude [2]. The shape of the payload compartment is, of course, critical to the final weight and size of the vehicle, but this must come from some sort of a preliminary vehicle configuration.

Subsystems

The following is a discussion of subsystems and accompanying menus. The order of the subsystems is the same as that used in the current Shuttle program. The following discussion and descriptions should be considered as an overview of the WAMI program in which salient aspects of the program are identified and discussed. The program content is detailed and lengthy. The following discussions represent only highlights of selected details and insights into the basis for the program. The operating system and its location at Langley are delineated on page 12. Further, in the interest of reducing the complexity of this discussion, constants for subsystems are simply identified as capital C.

In regard to 'line-replaceable-units' (LRUs), such as power, avionics etc. the weight supplied by the vendor understandably does not include a weight allowance for integration into the vehicle. This figure usually amounts to about 20 percent of the vendor-supplied weight. For those subsystem constants derived directly from the current Shuttle, the installation weights are, of course, already inherently included.

Structure

A number of programs are available for the sizing and weighing of structure, one of which is described in reference 3. Such programs are essential for identification of innovative structural concepts and, in general, for more granular knowledge of structural mass properties. The many options for structure can be decided upon with the support of a structures program. For the main propellant tanks a structures program can be used to size and locate ring-frames and stringers. For wing surface panels, skin stringer or honeycomb sandwich are options. Once the details of the mass properties have been established by a structures program, these results can be input to a mass properties program in a complete or simplified form. In the example structure shown in the following for the WAMI program, all structure is input in a simplified form using the following equation:

$$\text{Weight} = C \times \text{Area}^{1.22}$$

Shuttle mass properties and geometries are used for the baseline values for all structure. For wings, the exposed planform area is used. For the tail(s), profile area is used. For nose fairings, intertank adaptors, and aft skirts, wetted area is used in the same equation. In order to obtain constants, the weight and appropriate area of a known structural element (such as that from the Shuttle Orbiter) is entered and the equation solved for the constant, C. The equation gives good results over a wide range of sizes and doesn't 'blow-up' at any level. By dividing both sides of the equation by area, trends in unit weights can be obtained as:

$$\text{Unit wt, } w = C \times \text{Area}^{0.22}$$

As one example, doubling the area of a given vehicle in the above equation raises unit weight only about 17 percent. The Shuttle wing is unique and is the only space transport available from which to obtain reliable historical mass properties data. The wing shape is centered around a very 'thick' NACA airfoil (i.e., ten percent) and a design condition of 2.5 g's subsonic maneuver. Compare this with a tactical aircraft that may have a 6 to 7 percent airfoil and 8 to 11 g's as the core design condition for sizing and stress. Several other factors contribute to the uniqueness of the Shuttle wing. For example, near its root, the standard airfoil shape is thickened slightly in order to allow sufficient room for the main gear. Still other factors that make it unique are:

The addition of half ribs in between main ribs to limit deflection of the skin for the installation of bond-on ceramic tiles

The use of aluminum honeycomb sandwich as surface skin in a limited area just ahead of the wheel wells

The use of some composites for internal structure in some of the wings

By using the Shuttle wing-mass-properties data as a starting point, the fidelity of any alternative for materials and shape, etc. is enhanced. It is interesting to note that just a change in thermal protection system could effect a change in wing weight.

For example, if 'fasten-on' metallic panels were to be used, all half ribs might be eliminated. The wing surface is no longer deflection-limited. In addition, a substitute material might be used for the wing that weighs more but has a higher (than aluminum) temperature limit. The new wing having fasten-on metallic panels would not have the bondline temperature limit that ceramics do.

Still another feature that adds to the 'uniqueness' of the Shuttle wing is that it has no distinct identifiable wing carry-thru. The Shuttle wing carry-thru is integral with the vehicle body. The weight penalty of the 'carry-thru' can only be identified as an estimate. This estimate is 600 lb for the material added to the body to transmit wing loads.

The current Shuttle tail (equipped with a split rudder for speed-brakes) is a reliable source for this element for planned future vehicles. For any new tail, sizing and weighing using analytical means would be, at best, arduous because of the intricacies of the added structure and brackets needed for the speed-brake function. These items are included in a portion of the tail that is coded 'structure.' The unit weight of such a tail is quite high compared to a conventional tail because of the addition of rudder-speed-brake accessory structure.

The body structure of the vehicle is broken down into the following items:

- Forebody
- Crew module
- Mid-fuselage
- Aft-uselage
- Engine thrust structure
- Body flap

The main propellant tanks are also, for convenience, classified as structure even though, for some spacecraft designs, they are not integral. (Main propellant tanks could have been coded under propulsion). Two fuel and two oxidizer tanks are provided for in the program. They are coded as oxidizer tanks #1 and #2, and fuel tanks #3 and #4. This allows for the modeling of a dual fuel vehicle when required.

In the program, the weight of propellant tanks is based simply on the product of a constant and tank volume. The assumption made is that the tank weight is principally driven by internal pressure. The constants for cryogenic tanks are baselined on the Shuttle ET hydrogen and liquid oxygen tanks and then tailored for a specific application. For instance, the Shuttle-ET-LOX tank has no stringers for carrying axial compressive loads; therefore, if the tank is located aft in the study vehicle, the menu constant must be modified by the amount of the estimated weight of added

stringers. Also, a factor is the outer skin gauge; an increase is necessary in order to render the tanks suitable for multi-use.

If the main propellant tanks are integral, this means that a substantial portion of the outer moldline area is taken up with the barrel sections of the tanks. If the tanks are non-integral, this poses no 'mechanical' problem for the program. It simply means that the forebody, mid-body, and aft fuselages will make up the entire body wetted area by adding in the area of the base heat shield.

An equation for crew module data is also derived from the Shuttle. A constant is obtained from knowledge of the present Shuttle crew cabin volume and weight, and an assumed crew of eight. As indicated above, propellant tank weights were assumed to vary linearly with tank volume. However, cabin weights are assumed to vary with the product of a constant and crew cabin volume to the two-thirds power. This is an assumption that the tank wall of a pressurized crew cabin has little to do with changes in cabin volume but is related to cabin wall area. Technically this is not true, but in reality, cabin interior details such as hand rails, flooring, cabinets, and partitions have the dominant influence and outweigh cabin wall thickness changes with size, or:

$$\text{Crew Cabin Weight} = C \times (\text{cabin volume})^{2/3}$$

Thermal Protection

Again, there are no simple analytical solutions available for estimating the weight of the entire thermal protection system. Where there are cutouts and doors, tile density is typically increased. Any 'bumps' in the outer moldline of the vehicle make it necessary to install in these regions higher temperature-capability-higher-density tiles. Again, baseline constants are based on the current Shuttle tile area-coverage figures and 'lessons learned' [4].

For the circular body vehicle, there is no canopy for crew (only flush viewing ports) and the orbital maneuvering system is submerged (Fig. 1). Also, there are no cross-feed doors for LH and LOX that require special thermal protection treatment. These advantages of a simplified body shape in regard to heating rate distributions can be factored into the thermal protection system constant [5]. The weight of the system is estimated using the following equation:

$$\text{Weight} = C (\text{entry weight/entry planform})^{0.67} \times (\text{thermal protection area coverage})$$

The exponential in the above equation is included in order to reflect changes in thermal protection system weight with entry planform loading. For example, the Apollo entry planform loading is about double that for the Shuttle. Assuming a ratio of two and the exponential of 0.67, this suggests that the Apollo thermal protection shield, in terms of unit weight, would be 1.6 times as heavy, on the average, compared to that for the Shuttle – but not double. Flow around an entry vehicle starts off typically as laminar then becomes mixed laminar-turbulent. When the transition occurs from laminar to mixed laminar-turbulent is completely unpredictable. In regard to plan-

form loading, entry drag coefficient is often included as a product with planform in the denominator. However, for a winged transport entering at 35 to 40 degrees angle of attack or a ballistic shape, the drag coefficient approaches values of unity; therefore, this parameter has been left out of the equation since it is not necessary for the accuracy sought.

In more general terms, entry is the process of converting the kinetic energy of the vehicle in orbit to heat at entry. For the lower planform loading, such as the newer proposals for Earth-to-Orbit transports, this is just a matter of 'spreading' the dissipation of the kinetic energy, based on mass and velocity of the vehicle in orbit, over a larger area during entry. For this reason, heat load per unit area on the average should be lower but peak heating rate higher. The information from a real 'space transport' such as the Shuttle is invaluable in developing baseline menus for future vehicles.

Recovery, Docking and Landing Systems

For this category, gear weight is simply taken as a constant times landed or recovery weight. From the Shuttle program, the gear weight is 3 percent of landed weight. (Actually the gear is now a less-than-three percent gear due to Shuttle weight growth.) A gear without brakes but a ground arrestor is listed as approximately 2 percent. If a runway landing is used, and differential braking is relied upon for steering augmentation, then ground 'arrestation' is not a viable option. To obtain a more accurate weight of conventional landing gear, other factors that would have to be included are sink rate, gear length, stroke, scrape angle etc. Parachutes are listed at an estimated 5 percent of landed weight.

Propulsion Systems

The main propulsion system weight is based simply on the assumption that it can be given by the product of total vacuum thrust times a constant. If vacuum thrust requirements are doubled then it is assumed main propulsion system weight doubles. In the menus, no effort is made to separate pressurization and feed system weights from the main engine weights. In reality, a large Earth-to-Orbit transport that does not have cross-feed, will have greater mass budgeted for much longer feed lines than Shuttle Orbiter. On the other hand, the cross-feed system on the Orbiter is estimated to weight approximately 2000 lbs and if not used on a new (larger) vehicle its weight penalty could be eliminated.

Again, baseline auxiliary propulsion system constants (both maneuver and attitude control) weights are modeled after the current Shuttle. Attitude control system is simply based on vehicle weight at insertion times a constant, or

$$W_{rcs} = C (\text{Insertion weight})$$

Understandably, in the menu lists, cryogenic engines and storage systems are heavier but the propellant quantities required are smaller because of the greater propulsion efficiency of the latter.

For the orbital maneuver system (or OMS), two terms are used – one term for the engine weight and a second for all the other support systems, i.e., pressurization, feed, and propellant tanks. The engine weight is based on the assumption that it must provide a thrust-to-weight of 0.06 based on vehicle on-orbit vehicle weight. All of the support systems are based on the propellant quantity needed for the designated on-orbit maneuver delta-V.

$$\text{Or Woms} = C1 \text{ Entry weight} + C2 \times (\text{propellant quantity})$$

Installation ‘Non-opts’ for Smaller Subsystems

For smaller subsystems (often referred to as ‘line-replaceable-units’ or LRUs) about 20 percent of the vendor-supplied weight must be added to account for installation and integration. Examples of smaller subsystems might include motor controllers, surface control actuators, computers etc. For those subsystem constants that are derived directly from the current Shuttle, the installation weights are already included.

Prime Power

Menu constants are provided for fuel cells, hot gas turbines, and batteries. Energy system weights, liquid or solid, are dependent upon average and peak power and the mission length. For a fuel cell set, the size of the generating unit is dictated by peak power and the storage dewars by the length of the mission.

$$W = C1(\text{peak power}) + C2(\text{average power}) \times (\text{lapsed mission time})$$

Again, Shuttle data is relied heavily upon to obtain mass estimating relationships for fuel cell power. Redundancy strategy is imbedded in the Shuttle derived constants. In other words, if two fuel cell sets are required to accommodate peak power but a third fuel cell is held on standby, then the constant used for weight is based on the weight of three fuel cell sets.

The Shuttle uses a different type of power for surface control and main engine gimbal actuation. It is in the form of hot-gas turbines that drive hydraulic pumps for the distribution of high pressure fluid to hydraulic actuators. Gimbal actuator weights are based directly on total engine thrust and surface control actuation on the total area of movable surfaces. The Shuttle is equipped with three hot-gas-turbine-driven pump units.

Hydraulic powered actuation is a good candidate for future shuttles in as much as the system has been space qualified and proven reliable on the current Shuttle. Even so battery power for actuation may be worthy of consideration. Surface control actuators are principally used only during reentry and main engine gimbal actuators only during ascent. Lapsed time for ascent is about 500 seconds and entry approximately 1800 seconds. The total lapsed time amounts to approximately

38 minutes. Compare this with the on-time continuous power required of fuel cells on orbit for an 8 day mission (i.e. 11,520 minutes).

For a normal mission, duty cycles for Earth-to-Orbit transports are 'light' – on-times are small fractions of lapsed times. For batteries to be competitive for actuation functions, they must be capable of delivering large amounts of power but only for extremely short periods. At least 270 Volt systems are needed in order for the electric actuators to be competitive with hydraulics. Batteries could never compete with fuel cells or solar panels over large lapsed times and high amperages.

Surface Controls

Again, baseline menu constants are derived from Shuttle. An estimate for the total weight of the system is given by the product of a constant times wing exposed planform plus profile tail areas, or:

$$W = C \times (\text{Exposed wing area} + \text{tail profile area})$$

Analytically, the horsepower/size of actuators should vary with rate and the products of surface control area and distance from the hinge-line to nominal (design) center-of-pressure – or roughly with a vehicle (size) dimension cubed, not squared. In the real world, moments of inertia of any vehicle increase exponentially with size decreasing its sensitivity to wind gusts etc. In addition, the larger planes such as cargo or large transports (and Shuttle) do not maneuver at the high rates that smaller aircraft do. The product of the movable-surface-area times a constant gives 'good' answers over a wide range of vehicles. Electric actuators (all requiring motor controllers) must demonstrate equal or better reliability than the hydraulic. When motor controllers are included in actuator weight, the electric actuator is heavier than the hydraulic. However, considerable savings in overall system weight for electric actuators accrue from savings in weight for actuator power supply and distribution systems.

Avionics

Avionic are difficult to model. The Shuttle has three avionics bays and five main data processing units. As part of a redundancy strategy, three of the units are operated on a voting system. Some work has been done to render computers 'fault-tolerant'. Avionics for all Earth-to-Orbit transports is assumed to be fairly insensitive to size (weight). The baseline menu constant and matching exponential were derived from the Shuttle with matching points on a vehicle weight plot that includes a small personnel carrier [6].

The equation is as follows:

$$W = C \times (\text{vehicle weight})^a$$

Environmental Control and Life Support

The environmental control and life support systems are sized by the amount of power being used by the equipment and the amount of heat given off by the crew. The equipment component is given by:

$$W = C \times (\text{Peak power required by equipment})$$

Two primary options are provided in the menu list for the above constant – one based on a closed loop freon system and a much smaller dry weight for an ‘open loop’ flash evaporator. For the closed loop freon system, radiator size/area would be directly driven by the peak heat rejection rate required. In regard to life support, it is assumed to be linearly dependent upon number of crew and lapsed mission time or:

$$\text{Life support} = C \times (\text{number of crew} \times \text{lapsed time in hours} + 0.055 \times \text{cabin volume})$$

The first term is based on weight of LIOH canisters (not now used on Shuttle but might be used in smaller spacecraft and shorter missions). The last term is the penalty for the storage of extra nitrogen for one cabin repressurization. Since nitrogen is not expended in the metabolic processes, losses are completely dependent upon allowances for leakage and complete loss of cabin pressure.

Personnel Provisions

Personnel provisions are simply sensitive to number of crew and amenities provided. The latter including such items as sleep stations (for extended duration missions), water and waste management systems. In this regard, three crew provision constants labeled strategic, logistics, and extended duration are provided (Example Menu No. X).

Vehicle Sizing

Vehicle sizing is achieved through a sizing loop. The program user must make an estimate for packaging efficiency based on a configuration, and a preliminary size (length) estimate. Known volumes are payload bay, crew compartment, and engine compartment, the latter based on vehicle length (Fig. 1). The body volume of the ‘point’ design must also be known. The program then iterates on vehicle length until the propellant fractions for performance dictated by a trajectory program are realized. No volume allocations are made for subsystems except for the main engines. Rather, it is assumed that there is enough ‘casual’ volume in wing cavities, wing-body fairings, the ogive nose section, and under tank domes for subsystems. The sizing equation is as follows:

$$\begin{aligned} \text{Body volume} = & (\text{propellant} + \text{payload} + \text{crew} + \text{engine compartment volumes}) \\ & \div \text{packaging efficiency factor} \end{aligned}$$

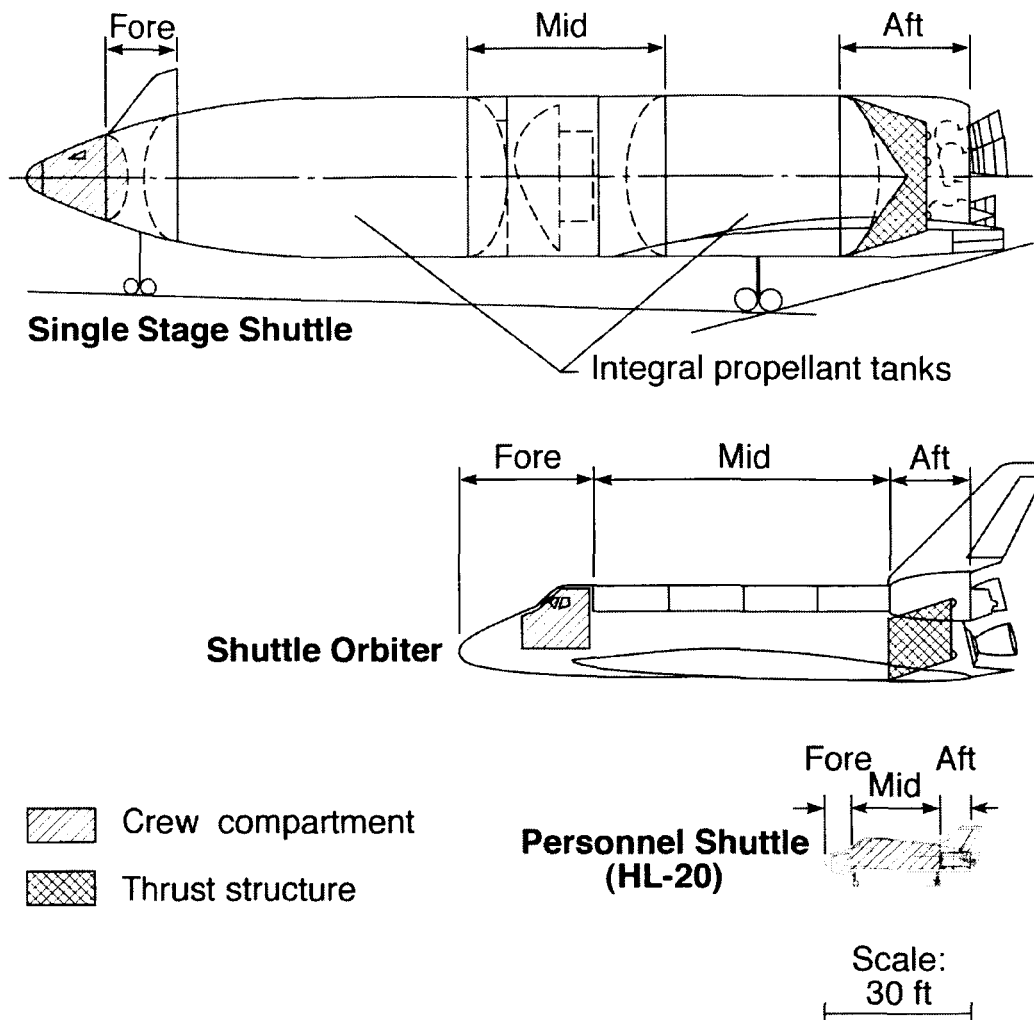


Figure 1. Body Structural and Volume Components Breakdown.

Body and propellant volumes are dependent variables based on vehicle length (L_{ref}). The program iterates until the above equation is satisfied. It should be evident that the packaging efficiency has a great deal to do with final vehicle size. Flat lifting body shapes, for example, with mattress tanks are typically low in packaging efficiency and high in structural weight. One factor that adds to weight is the necessity for adding fairings over the mattress tank lobes and extra large wings (or fins) to compensate for a more rearward progression of the structural center of gravity. More leverage is available in higher geometric L/D vehicles for adjustment of center of gravity by virtue of the more-forward locations of crew cabin, nose gear, and forward RCS module, etc.

Centers of Gravity and Moments of Inertia

Center of gravity locations for subsystems are all assigned values. They are taken from an in-board profile of the vehicle that has been divided into 10 stations along its reference length.

Some hints as to station location of subsystems on Earth-to-Orbit transports are given by the current Shuttle Orbiter (Fig. 2). These non-dimensional values become absolute values when multiplied by the iterated vehicle reference length from the sizing program.

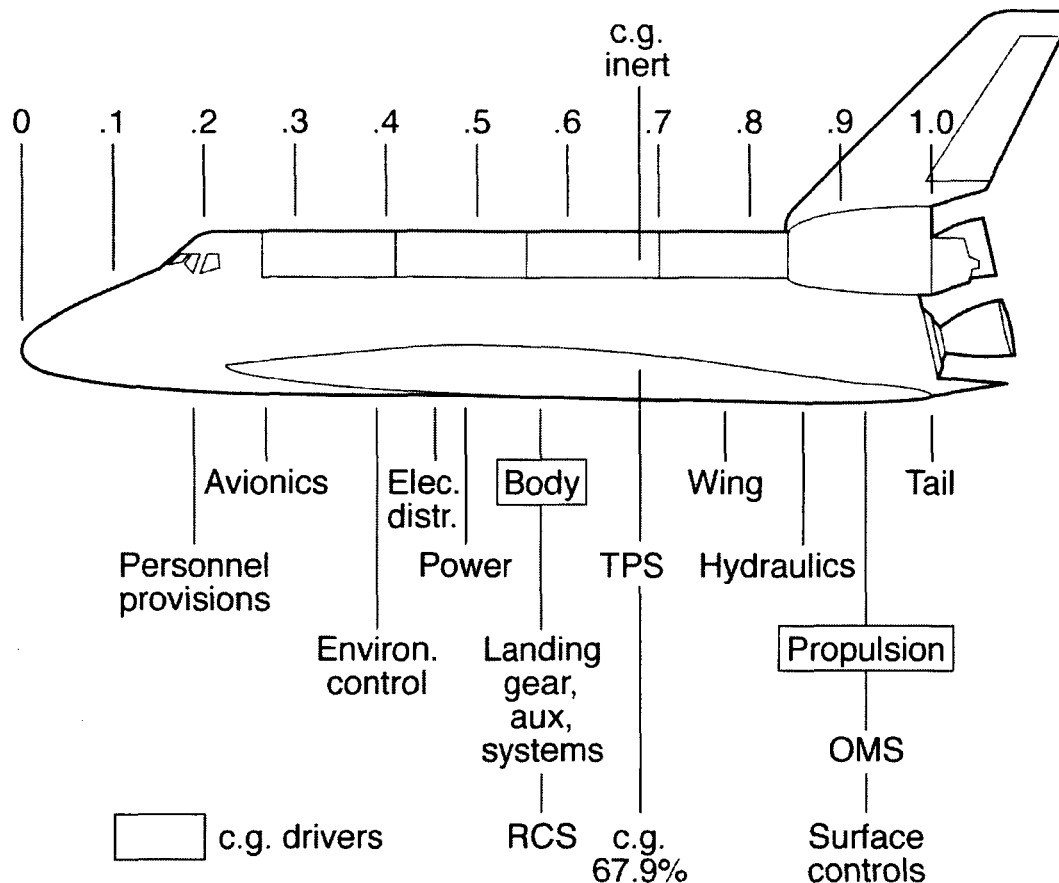


Figure 2. Shuttle Orbiter Composite Subsystem Centers of Gravity.

Individual subsystem moments of inertia are estimated from estimated values for radii of gyration [7]. Vehicle overall moment of inertia is obtained by using transfer formula relative to the vehicle calculated center of gravity. The fidelity of the above procedure can always be enhanced by utilizing calculated values for some subsystems, such as from the vendor. In any case, transfer distances are so large in these vehicles as to render miscalculations in radii of gyration of individual subsystems as of little significance relative to the accuracy of the final results. Some example subsystems with overall dimensions and weights are shown in reference 8.

Example Menu Lists

Appendix A lists a small segment of WAMI's user interface which specifies required constants for various subsystems. These are sub-menus and are logically arrived at from Main Menu Se-

lections. Menu List No. I is modeled around the assumption that all wings are clipped delta types with 55 degree sweep, 'thick' airfoils, and low design maneuver loads. In Menu List No. II, one of the constant options is for a crew cabin with no canopy and flush viewing ports to replace the traditional windshield. The crew can see the horizon during ascent and reentry but not forward during landing. A deployable TV camera would be used for the latter.

Menu No. III lists main engine thrust structure weights. An advantage is assumed in the form of reduction in weight by virtue of symmetry of the engine installations. Menus IV, V, and VI for propellant densities are core values needed for overall vehicle sizing and packaging of the vehicle. Two fuel options are needed for dual fuel single stage vehicles.

In Menu List No. VII, constants are provided for obtaining hydrogen tank weights. Single-use-Shuttle-external tanks provide a starting point for the identification of structural weights of integral-reusable-tanks. Several options are shown for landing/recovery systems in Menu List No. VIII. Vertical landing (using retro-rockets) would require the budgeting of fuel to be carried through the entire mission. The landing propellant would weigh much more than that of wings and traditional landing gear. The program, however, could be run for this mode by adding an artificial delta-V capability to the OMS for propellant quantity and an artificially large thrust-to-weight applied to the OMS engine to accommodate the landing maneuver.

PROGRAM OPERATING SYSTEM

WAMI was originally written in FORTRAN and was converted to C. It resides on a SGI belonging to the Vehicle Analysis Branch at NASA Langley Research Center. The machine on which it resides is at IRIX Release 5.3 operating system level. The code in its current form will not compile at a higher operating system level without modification.

SUMMARY REMARKS

The WAMI program is not exact but serves as a means of obtaining reasonably accurate mass properties data for candidate Earth-to-Orbit transports. It can also be used for personnel carriers that are delivered on a booster. The program represents a compromise between fidelity and the amount of time required to prepare inputs. Studies in wind tunnels of three methods of directional control for a circular body single stage shuttle illustrate the importance and strong relationship between aerodynamics and mass properties. A conventional rearward mounted vertical fin does most of the good things a directional device should do – such as provide stability in the lateral direction and a good location for speed-brakes [9-10].

A forward located all-movable-vertical fin (or dorsal), on the other hand, is estimated to weigh about one tenth that of a conventional tail and provides a certain amount of forward located 'ballast', and a lower drag during ascent. However, the dorsal is unstable in yaw – stability must be provided by an active control system. In addition, some means of energy management must be

added at the rear of the vehicle (such as side-of-body speed-brakes). Wing-mounted tip fins also can be used for directional control but they, too, do not provide stability in yaw. However, they could be used in a multi-purpose way, i.e., to perform the speed-brake function while also serving to provide directional control.

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Over the years, personnel in mass properties at the Johnson Space Center have helped us at Langley by supplying mass properties information on the Shuttle from their Shuttle monthly mass properties reports. The individuals who gave us help are too numerous to mention specifically. The reports supplied were typically out-of-date ones in which only a few weights had been changed on a monthly basis – but this had minimum effect on the level of accuracy of mass properties at which we were working in the prediction of the weights of future shuttles. For this help over the years for the benefit of the whole NASA agency, we are gratefully thankful.

APPENDIX A EXAMPLE MENUS

Example Menu No. I: Wing Group Structure

2.700 Super alloy honeycomb hot wing (no TPS req'd)
2.118 Conventional skin-stringer aluminum wet wing
1.577 Current Shuttle skin-stringer-honeycomb hybrid
1.229 Black aluminum composite wing
0.632 Advanced composite and advanced construction honeycomb

Example Menu No. II: Crew Module

2430 Aluminum skin-stringer; full windshield; sleep and eat quarters.
2120 Above with observation windows only
1000 Fighter plane cockpit
0 Unmanned vehicle

Example Menu No. III: Main Engine Thrust Structure

0.0024 Based on Shuttle (partial composite)
0.0020 Full composite
0.0015 Full composite, simplified geometry

Example Menu No. IV: Fuel 1 Density Constant, lb/ft³

(1) 50.0 RP
(2) 36.2 Propane
(3) 26.5 Methane

Example Menu No. V: Fuel 2 Density Constant, lb/ft³

(1) 4.43 LH
(2) 51.4 MMH
(3) 48.6 UDMH
(4) 62.5 Hydrazine4

Example Menu No. VI: Oxidizer Density Constant, lb/ft³

71.3 LOX

93.6 Fluorine

90.3 Nitrogen tetroxide

Example Menu No. VII: Hydrogen Tank Density Constant, lb/ft³

0.5918 Shuttle LH2 single flight

0.7100 Shuttle reusable

0.6000 Advanced reusable

Example Menu No. VIII: Landing Gear

0.0300 Based on Shuttle

0.0240 Advanced, partially composite

0.0217 Advanced composite with wheels, ground arrestor in lieu of brakes.

0.018 Advanced composites, skids in lieu of brakes

0.050 For parachutes

0.000 For non-recoverable vehicles

Example Menu No. IX: Surface Controls

1.210 Shuttle, 3000 psi hydraulic

0.990 8000 psi hydraulic

1.237 Samarium cobalt D.C.motors

Example Menu No. X: Crew Provisions

25 for strategic mission(less than 24 hours)

35 for logistics mission(less than 72 hours)

82 for extended mission(greater than 72 hours)

Example Menu No. XI: Seat Weight Constant

55 lb, fixed seat

415 lb, ejection seat

BIOGRAPHIES

Ian O. MacConochie received a BME '50 from the University of Virginia and a D.I.C. from the University of London 1958. His research at the University of London centered around lubrication with a background curriculum heavily orientated toward aircraft gas turbines. He spent a portion of his career in Academia, teaching mechanical engineering at Duke University (1953-55) and later at the University of South Carolina (1958-62). He spent 27 years at NASA Langley Research Center in space systems research and most recently as a consultant to NASA with SWALES, Inc. He is now serving as a Distinguished Research Associate with Langley. He is an Honorary Fellow with SAWE and past member of AIAA.

Nancy H. White received a Bachelor of Science degree in Mathematics from Longwood College and a Master of Science degree in Applied Science from William and Mary College. She retired from NASA Langley Research Center with 37 years experience and is currently under contract with NASA Langley through SWALES, Inc. as an operations analyst.

Janelle C. Mills holds a Bachelor of Science degree in Mathematics from Mary Washington College. She is a computer programmer with 20 years of experience in FORTRAN programming. She is currently under contract with NASA Langley Research Center through ViGYAN, Inc.